View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Bern Open Repository and Information System (BORIS)

DOI: 10.1111/1600-0498.12294

SPECIAL ISSUE ARTICLE

Centaurus WILEY

Vertical glaciology: The second discovery of the third dimension in climate research

Dania Achermann[1,2]

[1]Institute of History, University of Bern, Laenggassstrasse 49, Bern, 3012, Switzerland

[2]Interdisciplinary Centre for Science and Technology Studies (IZWT), University of Wuppertal, Wuppertal, Germany

Correspondence
Dania Achermann, University of Bern, Institute of History, Laenggassstrasse 49, 3012 Bern, Switzerland.
Email: achermann@uni-wuppertal.de

Funding information
Schweizerischer Nationalfonds zur Förderung der Wissenschaftlichen Forschung, Grant/ Award Number: PZ00P1_179883/1

SPECIAL ISSUE
Verticality in the history of science

GUEST EDITORS
Wilko Graf von Hardenberg and Martin Mahony

This Special Issue was selected by a dedicated ESHS committee after a public call for special issues.

Abstract

The history of climate research in the 20th century has been characterised by a crucial shift from a geography-oriented, two-dimensional approach towards a physics-based, three-dimensional concept of climate. In the 1930s, the introduction of new technology, such as radiosondes, enabled climatologists to investigate the high atmosphere, which had previously been out of reach. This "conquest of the third dimension" challenged the surface-oriented, geographical notion of climate patterns and opened up climatology to a three-dimensional approach, which deeply changed the character of climate research. Two decades later, by drilling deep into polar glaciers and using the downward vertical dimension as an archive of the earth's history, ice core scientists began to reconstruct past climates layer by layer. The data retrieved in deep glacial layers contributed crucially to a temporal expansion of climate history far beyond human timescales. However, the inaccessibility of glaciers and the practical challenges of bringing fragile fragments of ice into transnational networks of scientific exchange meant that this vertical extension of climate knowledge production proceeded through a range of new scientific practices, and was shaped by new forms of international collaboration. Furthermore, this vertical approach to glaciers also asked for a new understanding of glacier volume. Drawing on archival and printed sources, I argue

source: https://doi.org/10.7892/boris.139451 | downloaded: 27.12.2020

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.
© 2020 The Authors. Centaurus published by John Wiley & Sons Ltd.

that ice core research represented a second discovery of the third dimension, this time downwards into the depth of the earth's surface, but again with decisive consequences for the research practice, for collaboration politics, and for understandings of climate, spatially as well as temporally.

KEYWORDS

glaciology, history of climate science, ice cores, verticality

1 | INTRODUCTION

The history of climate research in the 20th century has been characterised by a crucial shift from a geography-oriented, two-dimensional approach towards a physics-based, three-dimensional concept of climate. Until the early 20th century, the dominant approach was regional. "Classical climatology," as it was called, focused on the two dimensions on the earth's surface. It was not only the lack of instruments that limited the scope. Climatology was a heterogeneous discipline, which included data and methods from geography, meteorology, history, and physics. But it was traditionally rooted in a geographical mindset: the spaces of interest were the spaces inhabited by human beings. Consequently, neither the oceans nor the high atmosphere were of major interest. These spaces were also hardly accessible. Attempts to include large-scale atmospheric processes in the discipline were made towards the end of the 19th century.[1] However, empirical data from mountain weather stations or balloon measurements remained scarce. Accordingly, these attempts remained largely theoretical. The major ambition of 19th-century climatologists, such as Julius von Hann or Wladimir Köppen, was to collect as much meteorological data measured close to the earth's surface as possible in order to categorise the different regional climates of the earth. While the meteorology of the 19th century tried to explain atmospheric phenomena with physical laws, classical climatology built mainly on its empirical, descriptive dataset.[2]

Only the introduction of a new technology enabled the vertical extension upwards. In the 1930s, radiosondes attached to balloons gathered an unprecedented amount of empirical data on wind speed, temperature, air pressure, and humidity from the high atmosphere. The focus upwards offered new causal explanations of climate phenomena, like the jet stream or the monsoon.[3] This vertical extension challenged the hitherto "surface-oriented" character of climatology.[4] New data could confirm the theories of a dynamic atmosphere developed by physicists and meteorologists. The empirical surveying of the third dimension profoundly changed the character of climate research; German climatologist Hermann Flohn called it the "conquest of the third dimension."[5] The human being was no longer the beginning and end point of climatological interest and understanding. The focus of research shifted from regional to large-scale climate patterns. This first discovery of the third dimension was a pivotal moment in the history of climatology.[6]

Three decades later, around the same time as computer modelling entered the scene of climate research (and changed it fundamentally), climate drew the attention of a research field that until then had been hardly connected to it: ice research. From the late 1950s onwards, geophysicists began to reconstruct past climate by drilling deep into

[1] See Coen (2018); Lehmann (2015); White (2015); and others.
[2] Fleming (1998); Heymann (2010); Heymann & Achermann (2018); Nebeker (1995, p. 48).
[3] Flohn (1949); Flohn (1950, pp. 143–144).
[4] Köppen (1895, p. 619); Heymann (2018, p. 4).
[5] Flohn (1951, p. 210).
[6] Heymann (2018, p. 4); Heymann & Achermann (2018, p. 608).

polar glaciers. In doing so, they adopted the archaeological practice of “downward destruction and upward reconstruction.”[7] This discovery of the glaciers' depth as an archive of climate's deep history strongly influenced the understanding of climatic behaviour in time. The development of ice core paleoclimatology, with its vertical approach, led to important changes in both glaciological and climatological research practice. Furthermore, it contributed to a new understanding of climate as a global and potentially rapidly changing condition. The study of ice samples retrieved from the depths of glaciers therefore initiated what I call the second discovery of the third dimension in climate research—this time not upwards, but downwards.[8]

In this contribution, I will examine the development of ice core paleoclimatology and analyse how this discovery of the third dimension downwards changed climatological and glaciological research practices. As Alessandro Antonello and Mark Carey recently pointed out, temporalities in the history of geology in the 18th and 19th centuries are well studied, but there is a lack of such studies for the post-war earth sciences.[9] With this paper, therefore, I also aim for a better understanding of how ice coring has influenced the temporal concept of climate and climate change.

2 | TURNING THE VERTICAL INTO TIME

In the first decades of the 20th century, glaciers were mainly studied by geologists, who consequently focused on the geological: They investigated the movements of glaciers and their impact on erosion and geomorphology, guessed glacier volumes, and put much effort into the surveying and mapping of glaciers.[10] “As a result,” Swiss glaciologist Henri Bader explained, “we know where the world's glaciers are, what they look like, the dangers they threaten, and the morphological and geological consequences of their presence.”[11]

In 1930, German explorer Alfred Wegener (1880–1930) set out on his third (and last) Greenland expedition. Part of the small research group of four was German glaciologist Ernst Sorge (1899–1946), who was also interested in studying glacier dynamics. While digging a snow pit for their quarters at Station Eismitte, Sorge examined the different snow layers. He noticed that they were chronologically ordered: the newest snow was on top; and the further down he dug, the older the snow layers were. Moreover, the layers were neatly horizontal and undisturbed. Due to the pressure from above, the older snow showed a higher density than the newer snow further up. Comparing the density and amount of the snow in each layer, Sorge was able to identify how much it must have snowed during the past 20 winters.[12]

A few years later, Swedish glaciologist Hans Ahlmann (1889–1974) started to consider glaciers in relation to climate. On his expeditions to the polar glaciers in the 1930s and 1940s, Ahlmann observed the rapid retreat of glaciers and theorised it was due to a warming climate. He therefore considered that glacier volume informed about contemporary climate change. However, Ahlmann was not interested in theories of climate warming that were discussed in other disciplines.[13] Like Sorge, he turned towards depth. On his Norwegian–Swedish expedition to Spitzbergen in 1934, he dug and drilled 10 m into the glacial surface in order to study the transformation downwards within the snow cover, from snowflakes into ice. The intermediate stage of this process—compact snow that has outlasted more than one winter—is called “firn,” which is why Ahlmann called this transformation process “firnification.”[14]

[7]Simonetti (2013, p. 90).
[8]The notion of “verticality downward” was also used by Esa Ruuskanen (2018, p. 35) for describing the exploitation of boglands in the mid-19th century, when these lands were no longer perceived as a horizontal space only. The Irish chemist Sir Robert Kane introduced the idea of reaching also for the depths of the boglands, where he expected huge amounts of turf to be used for a more effective energy production.
[9]Antonello & Carey (2017, p. 189).
[10]Bader (1949); Robin & Swithinbank (1987).
[11]Bader (1949, pp. 1309–1314).
[12]Sorge (1935). See also Martin-Nielsen (2013, pp. 33–37).
[13]Sörlin (2009, p. 103).
[14]Ahlmann (1935, p. 101).

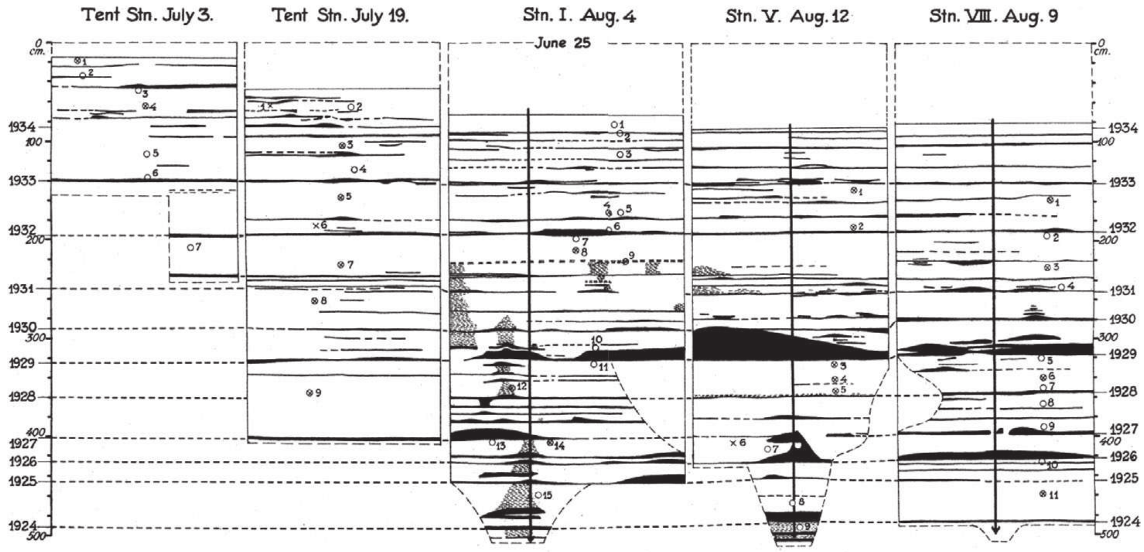


FIGURE 1 Ahlmann's vertical description of the snow and ice layers of five different ditches. Black indicates ice. The further down it goes, the higher the pressure and thus the icier the layers. From “Contribution to the Physics of Glaciers,” by H. W. Ahlmann, 1935, *The Geographical Journal*, *86*, pp. 102–103. Reprinted with permission of the Royal Geographical Society

Even if the thickness of the ice layers varied, Ahlmann noticed that the layers remained horizontal. With this study, and confirming Sorge's observation of the undisturbed snow layers, Ahlmann considered the depth of glaciers as “calendars, comprising the years 1924–34, in which every annual layer corresponded to the accumulation surplus of one year.”[15] For these upper parts of a glacier, it was easy to date the layers by simply counting the seasonal boundaries (Figure 1).[16] After Ahlmann's study, the stratigraphy of glacial snow was systematically included as a new dimension for temporal snow and ice studies.

The concept of verticality as a time indicator was not new per se. It emerged in geology in the early 19th century and marked an “epistemic break” in the field.[17] Georges Cuvier and Alexandre Brongniart in France and William Smith in England discovered at the same time that specific groups of fossils are found in specific “strata” (layers) that indicate different epochs in the earth's history. Thus, the earth had a “deep history” represented in a specific succession of fossils in geological layers. The discovery of stratigraphy helped geologists to understand the earth's crust as an archive.[18]

Growing out of a geological culture, the principle of stratigraphy was familiar to glaciologists. However, until then, it had not mattered, since it did not seem to have any importance for the classical glaciological research interest focusing on volume and dynamics. Stratigraphy only became a topic of interest in glaciology in the 1930s with the question of firnification, which connected the vertical axis directly with time. In the 1940s and 1950s, such firnification or “snow metamorphosis” studies were moved to the very top of research agendas, and more and more attention was directed towards the interior of glaciers.[19] More glaciological expeditions than ever headed towards the polar regions, and the stratigraphic method of digging and drilling into the glacial snow cover in order to study the firnification process quickly spread.[20] However, only the very top layers were necessary for studying this transformation process from snow into ice.

[15]Ahlmann (1935, p. 101).
[16]Lorius et al. (1992, p. 227).
[17]Sepkoski (2017, p. 57).
[18]Sepkoski (2017, p. 60); see also Irvine (2014, p. 162).
[19]The term “snow metamorphosis” was coined by Henri Bader in Switzerland (Bader 1939) and internationally used as a synonym of Ahlmann's term “firnification”.
[20]Schytt (1954); see also Elzinga (2015).

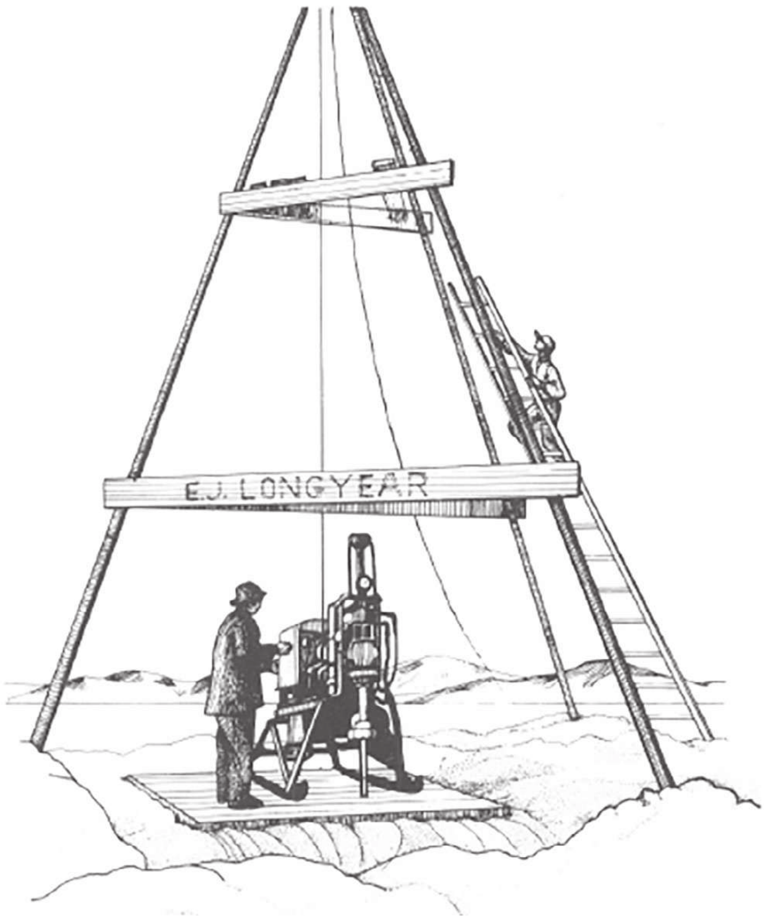


FIGURE 2 The rotary diamond drill used on the upper Taku Glacier, Alaska, during the Juneau Icefield Project, to bring a core up from a depth of 45–89 m. From "A Short History of Scientific Investigations on Glaciers," by G. K. C. Clarke, 1987, *Journal of Glaciology*, *33*, p. 13. Reprinted with permission of the International Glaciological Society. (Original photography of insufficient quality in Miller, 1951, p. 581)

While only the uppermost few meters were relevant for these novel firnification studies, traditional glaciologists, with their focus on the entire glacier's volume and dynamics, were keen to reach deeper depths. The interior of glaciers, however, was not accessible without appropriate technology. Whereas Sorge had arduously dug by hand and with shovels, the explorers from the 1950s onwards developed drills handy enough to be transported to the remote polar glaciers. One of these expeditions was the Norwegian–British–Swedish Antarctic expedition to Queen Maud Land (Maudheim Expedition, 1949–1952), initiated by Hans Ahlmann to study the effect of climatic fluctuations on the Antarctic glaciers. During this project, his mentee, Swedish glaciologist Valter Schytt (1919–1985), managed to core 100 m into the ice. At the same time, the group in the Juneau Icefield Project (JIFP) drilled 100 m into the Taku Glacier in Alaska.[21] The Expéditions polaires françaises (EPF) in Greenland succeeded in coring down to 150 m.[22] Usually at that time, this was done using machine drills with a mechanical rig. The JIFP group, for example, employed a rotary diamond drill (as in Figure 2). Valter Schytt examined a core that was heaved to the surface with this drill and observed variations in the ice structures:

> The holes bored in the ice provided cores for determination of the variation of density with depth, of changes in the crystal structure, and of the distribution of air bubbles and their internal pressure. All variations with depth were smooth; there were no layers where sudden changes occurred.[23]

The core retrieved with this drill was 8 cm in diameter, but the pieces were fragmentary and only a few cm long (Figure 3). The JIFP group analysed some of them in a simple, but heated, field laboratory right on the drilling site;

[21]Miller (1951).
[22]Heuberger (1954).
[23]Schytt (1954, p. 78).

FIGURE 3 Samples of the upper Taku Glacier core with bubbly ice from a depth of 73 m, retrieved in August 1950. From "Englacial Investigations Related to Core Drilling on the Upper Taku Glacier, Alaska," by M. M. Miller, 1951, *Journal of Glaciology*, *1*, p. 581. Reprinted with permission of the International Glaciological Society

the remainder were sent to cold rooms.[24] Due to its fragmentary state, however, the Taku core did not allow for stratigraphic studies, just like the cores drilled on the other expeditions.[25] Nonetheless, the main reason for such deeper drilling was not to get a core, but a hole. Sticks, thermometers, or other sensors were planted in these holes to observe deformation processes and record the temperature of the ice at different depths.[26] The primary aim of such ice studies was to gain a better understanding of the ice and glaciers themselves. On the rare occasions when a core or parts of it were retrieved from the deeper depths, it was mainly used to study the structure and behaviour of ice, not its stratigraphy. The climate in which Ahlmann and his colleagues was interested was not "in" the core, but in the behaviour of a glacier as an entity. Consequently, most of the time the focus of these drilling projects was on the borehole and not on the core. The latter normally melted during the drilling. This focus began to change in the 1950s, however, when researchers began to consider glacial ice as an archive of past climate.

3 | THE CLIMATE IN THE ICE

In 1953, Danish physicist Willi Dansgaard published a study that initiated what I am calling the second discovery of the third dimension in climate science. The paper appeared in *Tellus*, a new but soon-to-be major international journal for meteorology.[27] Dansgaard was a geophysicist with an interest in radioisotopes. He had set up a mass spectrometry laboratory at the University of Copenhagen where he studied the ratio of two different oxygen isotopes in precipitation ($\delta^{18}O/^{16}O$). He knew that the lower the air temperature was, the smaller was the ratio of the heavier ^{18}O to the lighter ^{16}O isotope in the rainwater. Identifying this ratio allowed him to determine the temperature during the rainfall.

[24]Langway (2008b, p. 105).
[25]Langway (1967, p. 4–5); see also Langway (2008b, p. 103).
[26]See, for example, Clarke (1987, p. 11).
[27]Dansgaard (1953).

Dansgaard soon developed the idea of studying very old ice by determining its age with the radiocarbon (C-14) dating method and then reconstructing the air temperature at the time when this ice fell to the earth as precipitation.[28] Radiocarbon dating had been introduced by U.S. chemist Willard Libby a few years earlier, and attempts to also use it for the dating of ice samples followed. Dansgaard saw "the possibility … to determine climatic changes over a period of time of several hundreds years of the past."[29] He was not a chemist, glaciologist, or climatologist by training, nor did he have any particular interest in climate to begin with.[30] But he recognised the benefit in combining his isotope technique with the radiocarbon dating method in order to gain knowledge about former climatic conditions. It was a crucial step in broadening academic interest in glacial ice and bringing its studies into the vicinity of climate research. But the question was: how could Dansgaard access such ice? The cores drilled for the study of glacier dynamics were usually disposed of because there was little interest in them, meaning that ice for C-14 and oxygen isotope studies was scarce. In order to study old ice samples, Dansgaard needed access to one of the rare ice cores that were kept. It was a few years before he saw an opportunity.

With the general boom of geosciences during the Cold War, glaciology enjoyed enormous financial support. Furthermore, in the midst of the growing interest in the Arctic region, the year 1957–1958 was announced as an International Geophysical Year (IGY). Under this umbrella, several nations, especially the USA and European countries, organised scientific polar expeditions.

The United States provided a particularly vast amount of funding for polar research, which was usually undertaken in a military context. Especially during the early Cold War, thanks to its location, Greenland was a major focus of U.S. geostrategy. Greenland had ceased to be a Danish colony in 1953 but remained part of Denmark as an autonomous province, so U.S. military activities took place in agreement with the Danish authorities. Snow and ice served as construction material for military bases on and under the ice.[31] It was therefore crucial to understand the dynamics of glaciers and the deformation process of ice and snow. For this purpose, the U.S. government had established the Snow, Ice and Permafrost Research Establishment (SIPRE; from 1961 onwards, the Cold Regions Research and Engineering Laboratory, CRREL) in 1949. In this context, glaciology was transformed from a geological science into an engineering science.[32] Snow and ice mechanics, as well as engineering and transport on the ice, were the most pressing research questions.[33] This meant the general approach was still geological and was concerned with the dynamics of the volumetric space of the glaciers. Climate was not a prominent interest of these glaciological studies.[34]

The cores drew more and more attention within the vast SIPRE projects as the range of research topics expanded. To construct facilities inside a glacier, it was crucial to understand the ice mechanics in the deeper layers as well. SIPRE researchers therefore experimented with new drill designs that were able to reach a depth of several hundred meters and to extract undisturbed cores.[35] In 1957, SIPRE researchers managed to drill more than 400 m down at Site 2, a U.S. military base near Thule in Greenland. The goals for this drilling project were "to study the physical and chemical nature of high-polar glacier ice in a nearly continuous profile" and "to provide information of value in the construction and preservation of undersnow structures on an ice cap."[36] For the first time, the core was the main reason for drilling, and it was therefore saved. It was 10 cm in diameter, and summer and winter ice layers were identifiable. The stratigraphy could thus be analysed, offering the possibility to study not only the structure and

[28]Dansgaard, W. (1958, Jan. 27), Letter to Børge Fristrup, Correspondence of Willi Dansgaard with Børge Fristrup, Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark (hereafter NBI).
[29]Dansgaard (1954b, p. 259). I thank Hubertus Fischer for directing me to this evidence.
[30]Lolck (2006, p. 24).
[31]For more on Camp Century as "City under the Ice" see Nielsen, Nielsen & Martin-Nielsen (2014).
[32]See Martin-Nielsen (2012; 2016).
[33]SIPRE (1950); SIPRE Research Program (1957–1958).
[34]More prominently, climate was an object of interest in regards of the extreme climatic conditions in the Arctic and how these could affect military actions. See SIPRE Research Program (1957–1958).
[35]"Ice Drills and Cores" (1957); SIPRE Research Program (1957–1958).
[36]Langway (1958, p. 217); SIPRE Research Program (1957–1958, p. 22).

behaviour of ice but also, among other things, atmospheric gas occluded in the layers.[37] The leading scientist, Chester C. Langway, was enthusiastic about the depth of the drilling, and he also envisioned the possibility of studying the different states of the atmosphere in the past:

> Never had the snow-ice mantle of any glacier been so deeply penetrated, nor had such an appreciable quantity of relatively large diameter ice core been recovered with such continuity …. Once the age-depth relation has been established, an opportunity exists to investigate any climatological trends and even meteorological disturbances that affected the world's atmosphere, such as major temperature changes, volcanic eruptions, or cosmic showers, which in turn, if historically recorded, provide us with very desirable index horizons."[38]

Since Greenland was under Danish authority, foreign expeditions in Greenland had to give Danish researchers access to their samples.[39] When Willi Dansgaard, in search of ice samples for his oxygen isotope studies, heard about the U. S. drilling project in Greenland, he approached the group and subsequently received some samples of this core that were up to 800 years old.

Just as the U.S. government, enlivened by its competition with the Soviet Union, invested an enormous amount of funding in glaciological research, European countries were very active during the IGY.[40] French and Swiss geophysicists initiated an international glaciological expedition to Greenland, the Expédition Glaciologique Internationale au Groenland (EGIG). Twenty-four scientists from France, Switzerland, Austria, the Federal Republic of Germany, and Denmark participated. The goal was "to obtain a better knowledge of the inner parts of the ice cap, its movement and behaviour from the surface down to the bedrock."[41] The drilling of ice cores was one of the methods used to gain such knowledge.

As is common in these international projects, the different nations contributed in different ways and the scientific topics were distributed among the participants according to their interests and expertise. French explorer Paul-Émile Victor, known to be very experienced in organising such an undertaking, led the expedition. The general glaciological, seismological, and hydrological work was also the responsibility of the French. The Swiss members were in charge of the glaciology of the ice sheet and the ice core studies.[42] The Germans were interested in geodesy and geophysics, while the few Austrian scientists measured heat balance and radiation. The Danes limited their focus to the glaciological and geodesic aspects of the coasts of Greenland, which was the smallest part of the project. Only one of the participants was actually Danish: Børge Fristrup, a geographer and glaciologist from Copenhagen, who was sent on the expedition as an observer for the Danish government.[43]

Willi Dansgaard and his fellow Danish scientists strongly disapproved of this lack of Danish ambition.[44] Nonetheless, Dansgaard saw an opportunity to obtain more old ice samples for his project of studying the isotope ratios of the past. He approached Børge Fristrup and asked him to organise some samples from Greenland; Fristrup was enthusiastic. As the Danish scientific liaison officer, he was eager to make the Danish contribution to EGIG more visible than had been originally planned. He encouraged the Swiss partners, who were in charge of the ice coring, to incorporate Dansgaard's request, even though that kind of research was not part of the program.[45]

---

[37]Langway (1958; 1967).
[38]Langway (1967, p. 7).
[39]Martin-Nielsen (2016, p. 95).
[40]On the geopolitical aspects of (U.S.) scientific research in Greenland, see Doel, Harper, & Heymann (2016).
[41]Haefeli (1959); quotation from Finsterwalder (1959, p. 542).
[42]An "ice sheet" is a dome-shaped glacier larger than 50,000 km^2. This type of glacier exists only in Greenland and Antarctica.
[43]Such governmental observers or "liaison officers" were installed by the Danish government to observe foreign activity in Greenland: Heymann et al. (2010, p. 33). For more details on EGIG, see Martin-Nielsen (2013, pp. 86–100).
[44]Martin-Nielsen (2013, pp. 87–88).
[45]Dansgaard, W. (1958, Jan. 27), Letter to Børge Fristrup; Fristrup, B. (1958, Jan. 28), Letter to Willi Dansgaard; Renaud, A. ([1962, Nov.]), EGIG 1957–1960, Groupe Suisse, Chapitre I, Introduction; all contained in Correspondence of Willi Dansgaard with Børge Fristrup, NBI.

On joint expeditions of this nature, not only the scientific tasks were distributed between the different nations, but also the logistical and technological contributions. Polar glaciologists heavily depend on technology to reach their research field. This was often the most expensive part of the project. Each institutional team was responsible for providing aeroplanes, drills, or chemicals, depending on their financial capacities.[46] In addition to the researchers, therefore, an important part of the EGIG team were technicians and mechanics with Arctic experience (almost all of them French), "without whom a modern expedition cannot be undertaken."[47] Although the scientific publications do not mention these technicians, their equipment and its maintenance was crucial. The EGIG participants considered their scientific goals as the continuation of Alfred Wegener's endeavours in Greenland. But instead of travelling on dogsleds like Wegener, EGIG relied on what they considered as "modern" means of transportation: mainly crawler vehicles and huge amphibious tractors ("weasels"), but also aeroplanes and helicopters.[48] The transportation on the ice sheet was critical, and EGIG benefitted considerably from the transportation experience and vehicle developments that emerged from the U.S. expeditions of the 1950s. Without appropriate vehicles, such as weasels, deep coring was impossible.[49]

France and Switzerland contributed the largest portion of the funding. France, for example, provided the aeroplanes, which were an important and expensive part of the logistics. Flying staff and regular supplies into the interior of the Greenland ice sheet took more than 600 flying hours with a large transport aeroplane. French expedition leader Victor was already experienced in handling the weasels, because on his last expedition in 1949, his U.S. colleagues had allocated their surplus weasels to him. The Swiss provided the snow removal machine with which all pits and trenches were dug. Unlike the scientific tasks, which were distributed clearly between the different national groups, the technical equipment was used collectively.[50]

In total, 45 men worked on the project in the summer of 1959, although only six men stayed on the inland ice in winter: a meteorologist, two glaciologists, a mechanic, a radio operator, and a physician. During the entire expedition from the west to east coast of Greenland, the Swiss members drilled several cores down to 30 m and sent them "home" for chemical, crystallographic, and morphological analysis. For the crystallographic studies in particular, it was important that the snow crystals did not change. The samples therefore had to be packed in boxes with dry ice in order to keep the temperature constant while they were shipped to Switzerland.[51]

4 | HORIZONTAL CHALLENGES: NETWORKS AND POLITICAL MANOEUVRING

Although the Swiss ice corers agreed to send samples to Copenhagen, cooperation from the Swiss representative André Renaud was not to Dansgaard's satisfaction. In October 1959, Dansgaard, still waiting for more samples from the drilling group, became impatient: "For God's sake, all that has to be done is to ram a stick into the earth, pull it up, and throw what is hanging on it into a bottle," he complained to Fristrup.[52] However, lifting samples from dozens of meters of depth was no easy task. It was necessary to ensure that they would not be "polluted" by snow from higher layers while they were lifted up through the borehole. Furthermore, the bottles in which they were stored had to be completely impermeable in order to prevent evaporation and secure the samples for the long journey from Greenland, via Switzerland, to Dansgaard's Laboratory in Copenhagen. To make matters even worse, there was a fire

[46] See Correspondence of Willi Dansgaard with Hans Oeschger, NBI.

[47] "… en lang række mekanikere og teknikere, som havde den fornødne arktiske erfaring, unden hvilke en moderne organiseret expedition ikke kan gennemføres." Fristrup (1960a, pp. 1–2), quotation on p. 2.

[48] Fristrup (1960a, pp. 1–2); Martin-Nielsen (2013, p. 47).

[49] Fristrup (1960b, p. 293).

[50] Fristrup (1960a, pp. 4, 7); Fristrup (1962, p. 298).

[51] Fristrup (1960a, pp. 5, 10, 15).

[52] "Herregud, alt hvad der skulle gøres er jo at stikke en stok i Jorden, trække den op og hive det der hænger på, ned i en flaske." (Dansgaard, W. (1959, Oct. 19), Minutes of telephone conversation with Børge Fristrup, Correspondence of Willi Dansgaard with Børge Fristrup, NBI.

at the cold house in Paris where the samples of the expedition were stored before shipping to Switzerland or Copenhagen, and many were destroyed.[53] Renaud therefore reminded Dansgaard that conditions in the field were far from the ideal setting of a laboratory: "One has to participate in the work of an expedition *in the field* in order to become aware of the fact that there are not the ideal conditions of a laboratory."[54] Renaud's implicit allegation that Dansgaard lacked field experience points towards conflicting expectations. Dansgaard was very well acquainted with Greenland's extreme conditions, since he had spent a year in Qeqertarsuaq from 1947 to 1948. Furthermore, he had participated in an expedition to a Norwegian glacier in 1958.[55] Thus, he must have known the conditions outside his laboratory. But when ordering his samples, he seemed to envisage just a single clean, vertical cross-section of a glacier. The scientists in the field, however, were exposed to the entire challenge of the three-dimensionality of field research, which did not consist simply of a smooth drilling downwards and heaving upwards, but included transportation to and from the drilling site, extreme weather conditions, and the technical and logistical troubles that come with collecting samples on polar field expeditions.

In the end, Renaud was still able to send Dansgaard a total of 223 samples, which Dansgaard analysed in his Copenhagen laboratory between November 1958 and October 1961.[56] Dansgaard, however, was still unhappy with the cooperation from the EGIG scientists (or the perceived lack of it). He therefore turned to a colleague in another network, one connected with SIPRE. Dansgaard complained:

> My own work is stagnant at the present time. EGIG has not taken all the ice cap samples I asked for, and the few ones they took have not been taken carefully. So I must face the possibility of being delayed a whole year untill [sic] I can go to Greenland and collect the samples myself. I know that the safest way to get things is to go for them yourself. However, this task was so easy that it seemed unnecessary to [waste] a whole summer for that alone. I wonder if you could help me?[57]

The situation between EGIG and Dansgaard shows that both the vertical and horizontal distances that the desired ice samples needed to traverse posed a practical challenge. The precious ice from Arctic glaciers were not only hard to retrieve vertically from the depth, there were also difficulties in transporting samples from the location of the borehole to laboratories in the home countries of the researchers. In order to remain as valuable research material, these samples had to be protected from pollution and changing temperatures through the use of clean and airtight containers, as well as by securing a continuous cold chain. Furthermore, the chain of cooperating persons had to be uninterrupted. When Dansgaard was not able to collect his own samples due to the remoteness of the glaciers, he depended on the cooperation of scientists from other laboratories and countries. It required a reliable scientific network, patience, and (more or less) diplomatic negotiations with every link in the chain from the borehole to the laboratory.

Towards the end of EGIG, plans for a continuation project took shape, and the Danish government wished to show a greater (scientific) Danish presence in Greenland to make its claim over the territory more visible. Consequently, Danish desire to participate in the subsequent EGIG II grew: "We want a part in the leadership in the explorations that is comparable to the fact that Greenland is Denmark."[58] There was a heated debate within the EGIG group about how Danish interests could be satisfied without too great a loss of autonomy from the EGIG participants from other nations.[59] At the same time, the Danish General Science Foundation (Statens almindelige Videnskabsfond) was willing to fund Dansgaard's studies, but on the condition that they would be carried out on

[53] Dansgaard (2005, p. 32).

[54] "Il faut avoir participé aux travaux *sur le terrain* d'une expédition pour se rendre compte que l'on n'y rencontre pas les conditions idéales des laboratoires." Original emphasis. Renaud, A. (1959, Nov. 19), Letter to Willi Dansgaard, Correspondence of Willi Dansgaard with André Renaud, NBI.

[55] Dansgaard (2005, pp. 18–29).

[56] Dansgaard, W. (1962, March 24), Letter to André Renaud, Correspondence of Willi Dansgaard with André Renaud, NBI.

[57] Dansgaard, W. (1959, Oct. 31), Letter from Dansgaard to Marchall [William Marshall], Correspondence of Willi Dansgaard with CRREL/Chet 1959–66, NBI.

[58] Brun, E. (1961, May 9), Meeting Minutes, Correspondence of Willi Dansgaard with Børge Fristrup, NBI.

[59] See EGIG Meeting in Copenhagen (1961, May 8–9), Meeting Minutes, Correspondence of Willi Dansgaard with Børge Fristrup, NBI.

expeditions explicitly identified as Danish.[60] Dansgaard planned to pursue research on ^{32}Si and ^{18}O, which would be very expensive as a purely Danish undertaking. EGIG II could divide those costs between several institutions. But Dansgaard's experience with EGIG I made him believe that this kind of research would be done under Swiss leadership, and its results would be considered as Swiss contributions rather than Danish ones, a possibility he was unwilling to accept. In addition, if Dansgaard's project became a part of EGIG II, Denmark was supposed to contribute to the costs of the expedition. But if Dansgaard declined the new cooperation with Renaud and EGIG II, he feared that his efforts in Greenland would become redundant.[61] A compromise was sought to bypass these political obstacles. In September 1964, the Danish, Swiss, and French collaborators met in Copenhagen to discuss the following possibility: the Danes would arrange for a (Danish) expedition by ship, and the Swiss would contribute financially. “An arrangement like this would keep our expedition as a Danish enterprise, which the funds will appreciate, at the same time both EGIG and we get the benefit of mutual scientific and financial support.”[62] Due to the enormous cost of polar expeditions, the complexity of the international politics, and the geostrategic importance of Greenland, such political manoeuvring was characteristic of post-war ice core expeditions.

At the same time as plans for a second EGIG were being debated, a Swiss physicist was experimenting in his laboratory in Bern with the study of the tiny air bubbles in glacial ice. Hans Oeschger (1927–1998) found a new way to extract the CO_2 contained in the tiny air bubbles. He managed to analyse it in a way that required much less ice than the former method.[63] Furthermore, Oeschger developed a method to melt the ice on-site with an apparatus that could in principle be carried through the Arctic. Dansgaard saw the opportunity for cooperation, not least because once Oeschger had melted the ice for his CO_2 analysis, it was still usable for other studies, such as Dansgaard's ^{32}Si research. As such, the highly valuable ice samples could be used twice. Despite such promising ideas, and numerous phone calls and letter exchanges, Dansgaard's and Oeschger's plans proved difficult to carry out. It seemed too challenging to either transport so much ice to a melting machine or bring the melting machine to the inland ice. Their joint planning dragged on.[64]

5 | GOING DEEP

While Camp Century was built and used as a U.S. military research base in Greenland (1959–1967) several more cores were drilled under the auspices of U.S. geophysicist Chester C. Langway. With a thermal coring drill, 26 m long and weighing 70 tons, his team drilled at the site of the Camp, which provided logistics and a sophisticated infrastructure. In 1966, using an electro-mechanical rotary drill, they reached the bedrock. A similar attempt to drill a deep core in Antarctica later the same year resulted in the loss of the drill in the depths. But the Camp Century core, as the first really deep core, was a sensation. It was not only the deepest core ever drilled, it also showed that the Greenland inland ice sheet was at this site frozen to the bedrock and not floating on a thin melt-water layer.[65]

Willi Dansgaard did not want to let this chance pass by without having laid hands on the samples from Camp Century. He wrote to Langway, who agreed to send Dansgaard samples from one of the smaller cores. Again, as they were unable to be present at the drill site, the Copenhagen group depended on the reliability of others. The packing and shipping of the samples was delayed for weeks and months. Dansgaard felt under pressure from the Carlsberg Foundation, who were funding his research, and became increasingly impatient. Eventually, in January 1968, the first samples from Camp Century arrived in Copenhagen filled in plastic bottles and packed in dry ice.[66] Due to the

[60] Dansgaard, W. (1964, Nov. 27), Letter to Hans Oeschger, Correspondence of Willi Dansgaard with Hans Oeschger, NBI.

[61] Dansgaard, W. (1963, Nov. 19), Letter to Einar Andersen, Correspondence of Willi Dansgaard with André Renaud, NBI.

[62] Dansgaard, W. (1964, Nov. 27), Letter to Hans Oeschger, Correspondence of Willi Dansgaard with Hans Oeschger, NBI. Eventually, Denmark and Dansgaard became more substantial contributors to EGIG II, which was carried out from 1967 to 1968.

[63] It reduced the amount of ice from 10–20 tons to 1 ton (Oeschger, Adler, & Langway, 1967).

[64] See Correspondence of Willi Dansgaard and Hans Oeschger, NBI.

[65] Dansgaard (2005, p. 84); Langway (2008b, p. 107); Fristrup (1977, p. 304). On technical details of the drills, see also Langway (2008a).

[66] See Correspondence between Dansgaard and Chester C. Langway, in Correspondence of Willi Dansgaard with CRREL/Chet 1959–66, NBI.

success and remarkable speed of their subsequent analysis and the political conditions for research in Greenland, the Danes also got access to samples of the sensational Camp Century deep core.[67] It had a length of 1,400 m and contained a neat chronology covering about 100,000 years.

Shortly thereafter, Dansgaard sent one of his researchers, Jørgen Møller, to CRREL in New Hampshire in order to have him closer to the cores and to have him bring almost 1,000 samples back to Copenhagen.[68] Thanks to his access to the Camp Century core, Dansgaard could reconstruct the $\delta^{18}O$, and hence the temperature changes, for a period back to the year 300 AD. In this time series he detected climatic oscillations on roughly 120-year cycles (Figure 4).

With these results, the group was eventually left in no doubt that ice could serve as a detailed archive of past climate variables over a long period of time. The chronology of such deep ice cores is longer than that of tree rings but shorter than those of some ocean sediment cores. However, ice cores are more continuous and show a higher temporal resolution than any other known natural archive. Later on, with studies on CO_2, they found a distinct correlation between the air temperature and the CO^2 content of the air bubbles.[69]

However, the stratigraphic concept in ice core paleoclimatology is not as straightforward as it might seem. Glaciers are constantly on the move. The annual ice layers develop in the upper areas of the glacier. There, in the so-called accumulation zone, the amount of new snow falling is higher than the amount that melts in summer, resulting in a vertical movement of ice downward; every winter, a new layer of snow compresses the older ones. The increasing pressure squeezes the air out and transforms the snow into firn and ice. With time, the snow/ice therefore moves vertically down towards the bedrock. On this vertical "journey," the layers are also stretched horizontally and become thinner. The closer to the bedrock, the thinner the layers become. What began, for example, as a 1 m-thick snow cover may end up as a 1 cm layer of ice at the bottom of the glacier.[70] At this depth, it can be impossible to identify the layer boundaries. Radiocarbon dating of CO_2 in the ice was attempted from the 1960s onwards, but it needed a minimum amount of ice that was not older than 40,000 years. The deep ice layers of the Camp Century core were too thin and too old for this. This posed a challenge to Dansgaard's group because they needed to know the age of all layers to reconstruct the oxygen isotope (and thus temperature) changes. Hence, they needed another dating method. If they knew exactly how the ice flowed within a glacier, they could trace the "journey" of each layer through time and date its age without radiocarbon dating, just according to its location.[71] In this way, knowledge about the flowing pattern of a glacier became essential to dating the old ice layers. As such, for the Camp Century deep core, Willi Dansgaard and his colleague Sigfus Johnsen specifically developed a glacier flow model, with which they could determine the age of the ice according to its depth (Figure 5).[72]

Based on this new flow model for "cold" glaciers, the Copenhagen group could also date the deep layers of the Camp Century core and determine the changing oxygen isotope ratios over a period of 100,000 years. By plotting this ratio against time (Figure 6), they dated the end of the last glacial period and the beginning of the Holocene quite precisely to 12,000 years ago.

Like Dansgaard, Oeschger was a physicist and had not been trained as a glaciologist or a climatologist. Together with their colleagues, however, Dansgaard and Oeschger discovered glacial ice as a highly interesting archive of paleoclimate information, much like Ahlmann's idea of a "calendar." But unlike Ahlmann, they were not primarily interested in the glacier as a volumetric study object, but rather in the ice as carrier of climate information. Their

[67]Correspondence of Willi Dansgaard with CRREL/Chet 1959–66, NBI; Correspondence of Willi Dansgaard with Camp Century Borkerne, NBI.

[68]Dansgaard, W. (1968, Aug. 9), Letter from Dansgaard to Chester C. Langway, Correspondence of Willi Dansgaard with CRREL/Chet 1959–66, NBI.

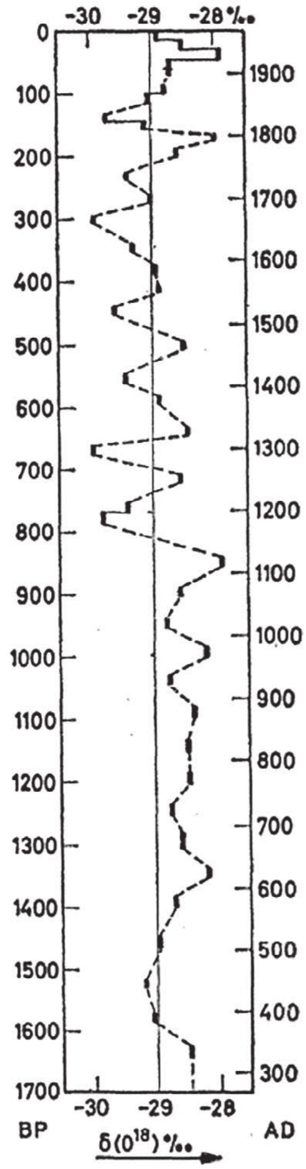
[69]Among others, see Neftel, Oeschger, Schwander, Stauffer, & Zumbrunn (1982).

[70]For more details on the interior of a glacier, see Alley (2000, pp. 33–37).

[71]Dansgaard (2005, p. 56).

[72]A few years earlier, British glaciologist David Nye had already developed such a glacier flow model. His model was designed for glaciers that were temperate enough to slide on the bedrock. The temperature of the bottom of the Camp Century glacier, though, was $-13^{\circ}C$. It was therefore frozen to the bedrock and the lower ice layers barely moved. This had important consequences for the flow pattern. Dansgaard and Johnsen based their new model for such cold glaciers (also called the "sandwich model") on Nye's model but took the varying velocity of the different layers into account (Dansgaard & Johnsen, 1969). At the same time, other research groups also began to develop computer models of glacier dynamics. For the Australian case and the role of William Budd, see Antonello (2018, pp. 136–137).

FIGURE 4 Reconstruction of oxygen isotope ratios going back 1,700 years with samples from the Camp Century ice core (1966). "BP" means "before present." From "One Thousand Centuries of Climatic Record from Camp Century on the Greenland Ice Sheet," by W. Dansgaard, S. J. Johnsen, J. Møller, & C. C. Langway, 1969, *Science*, *166*, p. 378. Reprinted with permission of the American Association for the Advancement of Science



interest shows how glaciology as a discipline was changing. With the new flow model and awareness of the thinning of the layers, the internal complexity of the glaciers became key to the interpretation of the ice core data. Until the 1950s, glaciology had relied heavily on empirical research in a geographical and geological field-research tradition, with little physics involved. Glaciers were studied primarily as a voluminous, three-dimensional object. The interest in stratigraphy, turning the vertical into time, and in the drilling of ice cores of at most 10 cm in diameter was basically one-dimensional, focusing on the one vertical axis. Snow and ice samples were studied in the laboratories as quasi-universal, giving evidence of the principles of the firnification process or of past temperatures. But the deeper the drills went, the more it became clear that the concentration on the vertical axis was insufficient. In order to understand the vertical ice samples, the whole glacier and its behaviour as a voluminous object needed to be taken into account. Thus, after a decade of focusing on the vertical, the volumetric dimensions of the glacier gained a new significance for the ice corers and raised new questions on the complex interior of different glacier types. What was needed was ice core research "in context." On the one hand, by producing knowledge on the stratigraphy of glaciers, ice core research made glaciology a science with a distinct vertical dimension. On the other hand, after expanding beyond its "vertical only" approach, it also enriched glaciology with theories on volumetric glacial dynamics.

Ice coring not only strengthened the vertical aspect in glaciology, it also expanded its disciplinary orientation. With the rising (political) importance and authority of geophysics, along with projects like SIPRE, glaciers moved

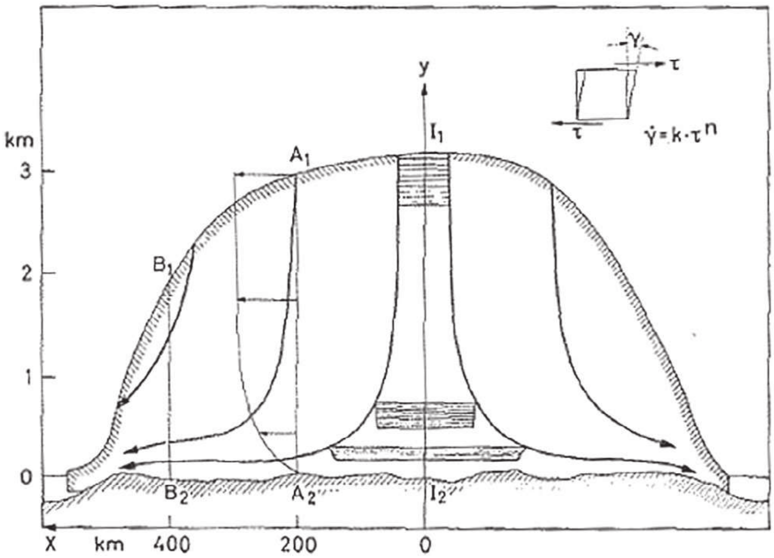


FIGURE 5 Simplified visualisation of the ice flow within a "cold glacier," such as the Camp Century glacier. The glacier is frozen to the bedrock, which is why its lower part moves more slowly than the upper part and the horizontal velocity is not the same along the vertical line. The lower ice layers are therefore older than those of the same depths in a "temperate" glacier that is not frozen to the ground. From "Isotop-undersøgelser af gletschere," by W. Dansgaard, 1967, *Fysisk Tidsskrift*, *65*, p. 19. Reprinted with the permission of the Danish Society for the Dissemination of Natural Sciences

more into the focus of physicists like Dansgaard and Oeschger. There was growing interest in using new measurement techniques based in nuclear physics, like the radiation counter and mass spectrometry, in glaciological research as well. With studies on fluid dynamics, sophisticated mathematical flow models, radiocarbon dating, and so on, the scope of glaciology broadened to include influential new physical approaches.[73] Even though the mapping and observing traditions of geological-geographical glaciology never disappeared, the field opened up to encompass a great number of new physical research questions and methods. Glaciological field research was complemented more and more by studies of ice samples in laboratories in the field, as well as far away from the field, which paved the way for a new science of ice core paleoclimatology.

6 | VERTICAL STRATIGRAPHY VERSUS HORIZONTAL ACCESSIBILITY

As mentioned above, the velocity of ice flowing downhill varies inside a glacier depending on depth, pressure, and friction on the bedrock. But it is also possible that the different snow layers are not preserved in the same way everywhere in the glacier, as the idealised model in Dansgaard's and Johnsen's flow model (Figure 5) suggested. They may distort, and the chronological layering can be destroyed. The case of a 2.7 million-year-old ice sample illustrates this problem well. Until recently, the oldest ice ever dated was drilled in 2004 at Dome C station in Antarctica. The core of a depth of 3,270 m preserved a continuous, vertical stratigraphic chronology of ice covering about 800,000 years.[74] But just a few years later, a group of scientists in the Allan Hills in Antarctica beat this record. They dated their ice sample to 1 million years ago.[75] In 2015, the same year that this sensational finding was published, the team returned to the same spot in order to drill even further into the ice. What they found was ice 2.7 million years old. However, both cores showed no continuous layering that would allow the ice to be dated by counting the layers or by measuring its distance from the ground. The layers were disturbed and the ancient ice was found close to the surface. Such cores do not offer a stratigraphy that allows for a reconstruction of climate variables over such long time periods. They are rather "climate snapshots": windows into the deep past without a continuous chronology or context.[76]

[73]See Blatter, Greve, & Abe-Ouchi (2010); Clarke (1987, p. 17); Seligman (1959).
[74]See, for example, Lüthi et al. (2008).
[75]Higgins et al. (2015).
[76]Yan et al. (2017).

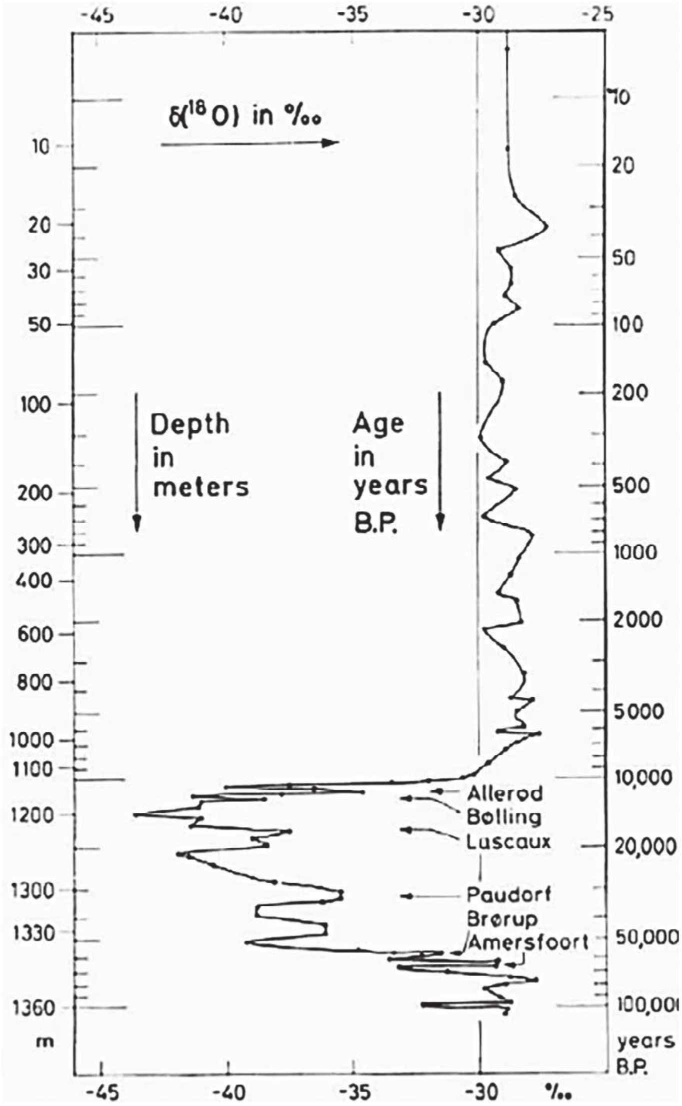


FIGURE 6 The depth of the Camp Century core (left axis) plotted against the age of the layers (right axis), based on the new flow model. The horizontal axis indicates the deviation of the $^{18}O/^{16}O$ isotopic ratio from that of standard mean ocean water in permille. "Allerød," "Bølling," "Lascaux," and so on indicate short warming periods during the last ice age, called "interstadials." From "A Flow Model and a Time Scale for the Ice Core from Camp Century," by W. Dansgaard & S. J. Johnsen, 1969, *Journal of Glaciology*, *8*, p. 221. Reprinted with permission of the International Glaciological Society

In order to drill ice cores that would cover as long a time period as possible, it was therefore essential for Dansgaard and Oeschger (as it still is today) to find the right spot to drill. Two factors were central for that. The first was the steadily improving knowledge of the interior of glaciers. The ideal drilling site was in an accumulation area in the higher part of an ice sheet. There should not be much motion inside the glacier to prevent layer disturbance, and the summer temperature should be cold enough to prevent melting of the newest snow layers. Second, the drilling location had to be accessible for the researchers, the technicians, and the logistical support of all necessary equipment and supplies.[77] This was predominantly a financial question. Sites where there was already a research station or military camp with existing infrastructure were therefore prioritised, as had been the case for Site 2 (400 m core, 1958) and Camp Century (deep core, 1966).[78]

These two factors, vertical glacier structure and horizontal accessibility, had to be weighed against each other, as the subsequent project of Dansgaard and Oeschger showed. They continued to collaborate in the 1970s and, together with Chester Langway, initiated a joint expedition to Greenland. "We are beginning to build up a great party now: Swiss-Danish-New Hampshire-Californian," Dansgaard rejoiced, "which is wonderful, if the budget can take it and, of course, if the budget gets strengthened by it."[79] It was important to find the balance between winning as many funding partners as possible and not taking too many collaborative partners (and hence costs) on board.

[77]Recently, a third factor has been identified: the ice sheet should not be too thick because the insolation of the bedrock would prevent the dissipation of geothermal heat and hence lead to a melting at the bottom of the ice sheet. Fischer et al. (2013). I thank Hubertus Fischer for directing my attention to this fact.
[78]Fristrup (1960c, pp. 89–90); Langway (1967, pp. 4–5).
[79]Dansgaard, W. (1970, Aug. 1), Letter to Chester C. Langway, Correspondence of Willi Dansgaard with CRREL/Chet 1959–66, NBI.

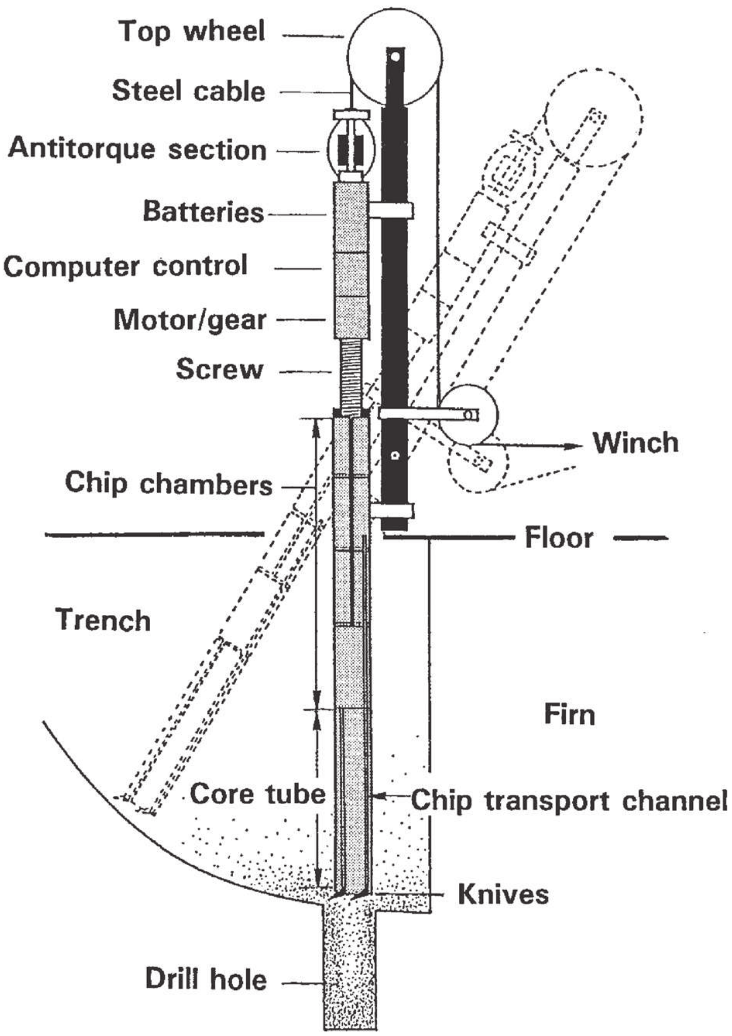


FIGURE 7 A sketch of the drill named "ISTUK," which was used for the DYE 3 deep drilling. It could be tilted between a horizontal and a vertical position by a hydraulic pump. It was less than half the size of the Camp Century drill (11 m rather than 26 m) and weighed only 1 ton rather than 70 tons. The comparatively small size allowed for transportation by airplane and required a much smaller shelter. From *Frozen Annals: Greenland Ice Sheet Research* (p. 84), by W. Dansgaard, 2005, Copenhagen, Denmark: Niels Bohr Institute. Reprinted with the permission of the Niels Bohr Institute, University of Copenhagen

In 1971, the three of them started the joint Greenland Ice Sheet Program (GISP). Extensive and expensive preparations were necessary to find the ideal site for deep drilling. The group made airborne radar depth-sounding surveys and geophysical and glaciological studies.[80] They took several cores to depths of a few hundred metres, and—after 7 years of preparation—eventually found the optimal site for a deep drilling in north-central Greenland. However, at this point, the U.S. National Science Foundation (NSF) decided that it would be too expensive to drill there.[81] Furthermore, if they wanted to drill deep, the GISP group needed a new drill capable of doing the job, since the U.S. group had lost theirs in Antarctica. Dansgaard used his well-honed negotiation skills to get funding for a new drill and the drilling operation: eventually, the Danish Greenland Commission agreed to pay for the construction of a new drill on the condition that the NSF paid for the first drilling, to which the latter agreed.[82] The Danes designed a new deep drill (Figure 7) and named it "ISTUK"—a composite of "*is*," the Danish word for "ice," and "*tuk*," Greenlandic for "spear" or "drill." But financial restrictions meant that the researchers had to choose the cheaper rather than the more promising drilling location; the DYE 3 site, which they settled upon, was simply easier to access.[83]

[80]Radar echo-sounding had been used since the 1960s to explore sub-glacial morphology. The sounding technique made it possible to "see" vertically through the ice cover and map the topography underneath a glacier. For more on radio-echo sounding of glaciers, see Turchetti, Dean, Naylor, & Siegert (2008) and Merchant (2020).

[81]Langway (2008b, pp. 109–110).

[82]Dansgaard (2005, p. 83).

[83]Langway (2008b, pp. 109–110). On the construction of ISTUK and the U.S.–European collaboration during GISP (and particularly on the break-up of the cooperation thereafter), see Elzinga (2012, pp. 95–100).

Drilling started in 1979 and reached bedrock in August 1981 at 2,037 m.[84] As a result of this Danish–Swiss–U. S. cooperation, and based on the knowledge gained from the Camp Century core, the GISP group proved that the Earth had undergone rapid climatic changes during the last ice age, which were later dubbed "Dansgaard-Oeschger events." It was the ultimate proof that climate had changed rather quickly in the past.

7 | PRACTICAL AND DISCIPLINARY CONSEQUENCES OF DOWNWARDS VERTICALITY: INSTRUMENTS AND NETWORKS

The downward vertical approach had major technological implications. Raised from the depths of glaciers with enormous financial and technological effort, ice cores have been exceedingly rare and valuable objects of investigation. Instruments, logistics, and collaboration were (and still are) prerequisites to getting access to them. When, from the 1950s onwards, the cores drew as much attention as the borehole, the focus shifted from the drilling itself to designing drills that would not destroy the cores.[85] Since climate, as we are aware today, changes in smaller and larger cycles of up to several hundred thousand years, deep cores with an undisturbed "event stratigraphy" have become very valuable research objects.[86] In order to reach such depths, the drills have played a leading role in ice core paleoclimatology. The deeper the desired ice was, the more sophisticated and powerful the drills needed to be. The ISTUK drill illustrates that it was not an off-the-shelf technology, but a central actor, carefully designed, adapted, and improved over several years and generations of drills, and thus worthy of being given a name.

The new research interest in ice cores caused a need not only for novel drills but also for instruments from other disciplines, such as Dansgaard's mass spectrometer and Oeschger's radiocarbon counter. Thanks to the vertical extension, these instruments from physics and geochemistry found a new scope of application in glaciology and climate science and helped the traditionally field-oriented discipline of glaciology to also become a technology-based laboratory science that incorporated physical and geochemical approaches and methods. The technological equipment was an important factor in making glaciology a vertical science.

Furthermore, information from ice cores proved to be highly valuable for calibrating climate models. From the 1960s onwards, and with the rise of paleoclimatology, the temporal scope of climate research scaled up to encompass tens and hundreds of thousands of years. At the same time, computer models served not only as heuristic instruments for better understanding the climate system, but were used more and more to make projections of future climatic changes.[87] While numerical weather forecast models can be tested against the actual weather development within a few days or weeks, it is not possible to compare the projections of climate models with the actual climate of a few hundreds or thousands of years in the future. But with knowledge about climate behaviour in the deep past, the models can be tested against a past climatic state. Thus, with its detailed and continuous event stratigraphy, ice core paleoclimatology fundamentally helped to improve climate models. In return, the growing importance of climate modelling and its need for paleoclimatological information stimulated ice coring practice. In addition to the dominant physical–mathematical approach, it was this interplay between climate modelling, ice coring, and several other fields of research that became characteristic of modern climate research as a highly interdisciplinary science.

The case of ice core paleoclimatology also shows the importance of the horizontal dimension to the success of the vertical. Finding the ideal site for drilling, as well as transporting instruments, staff, and ice samples on the ice and from there to overseas laboratories, was a demanding and costly undertaking. Such high costs were one of the most important drivers for international and inter-institutional collaborations. Such collaborations relied on a network that (horizontally) spanned several research groups, institutions, and countries. The research tasks and responsibility for transportation were divided and the costs could be shared. The Camp Century core was an exemplary

[84]Langway (2008b, p. 110).
[85]See also Clarke (1987, p. 14).
[86]Caseldine (2012, p. 331).
[87]See Heymann, Gramelsberger, & Mahony (2017).

case. The specific location of the drilling site, in geographical and political terms, brought the Dane Willi Dansgaard and the American Chester Langway together. "Willi had the isotopic methods to measure climate from a core but no core, and Chet had the core but not the method," commented Dangaard's colleague Jørgen Peder Steffensen on the foundation of their collaboration.[88] Just as the ice samples depended on an uninterrupted cold chain in order to stay valuable, so too did the researchers depend on a reliable chain of actors in order to get access to the ice, the instruments, and the methods.

In addition to the scientific networks, geopolitics played an important role. The Cold War setting and geopolitical power relations assigned a political function to research in the polar regions, particularly in Greenland, which was politically important due to its geographical position between the USA and the Soviet Union. An alliance with Denmark allowed the U.S. military to establish military bases in Greenland and to conduct glaciological (and other) research necessary for running military activities in this extreme environment. Thus, Cold War politics bestowed a political value on Greenland based on its horizontal territory and position between the two great powers. For their work, glaciologists and ice core scientists could rely on this military infrastructure, network, and funding. At the same time, the space underneath the glacial surface drew more and more military attention since it seemed to offer protection against hostile attacks and unwanted observation. It was the task of the glaciologists to provide the necessary knowledge that would enable such use of the space under the ice. Consequently, with their research, not only they enabled the Greenland territory to be approached as a horizontal space, but also helped to make it politically relevant as a vertical and eventually complex, voluminous, and three-dimensional space.[89]

8 | EPISTEMIC CONSEQUENCES: THE SECOND DISCOVERY OF THE THIRD DIMENSION

Besides these practical and disciplinary effects in the political context, the vertical approach in glaciology had also crucial epistemological consequences for climate research. These can be subsumed under three aspects that I will explain more closely: the extension of the temporal scale, the concept of abrupt changes, and the extension of the spatial scale.

The ice core drilling went deep, both literally and figuratively. The idea of "deep time," although a recent term, became popular in the geological community of the 18th century.[90] The earth's history seemed to exceed human (or biblical) history. The awareness of a deep history of the earth had revolutionary implications for the understanding of the status of human beings in the (history of the) natural environment. Besides, it implied that the natural environment has a history at all.[91] Ice age theories emerged in the middle of the 19th century. It was a question subject to lively discussion in the geology, physics, and astronomy communities.[92] Yet climatology, at the time, was little concerned with these theories. The vast majority of classical climatologists concentrated on smaller time scales of a couple of hundred years.[93] In the course of the growing dominance of physical–mathematical approaches to climate research in the 20th century, this attitude fundamentally changed. Ice core paleoclimatology opened up the time horizon towards an understanding of climate with a very long history.[94] It did not reinvent the idea of deep time. But the stratigraphic method in glaciology, combined with the dating techniques and isotope physics, filled this vague

[88] Jørgen Peder Steffensen (2020, Apr. 14), personal communication to the author.

[89] On the political importance of the vertical dimension of territory in general, see also Graf von Hardenberg & Mahony (2020).

[90] Irvine (2014). According to Rudwick (2005, p. 162), the term "deep time" was coined by John McPhee (1981). However, the idea of a very long geological earth history was already prevalent in 11th-century Persia (Irvine, 2014, p. 162).

[91] Rudwick (2005, pp. 1–2).

[92] See Krüger (2008).

[93] Heymann & Achermann (2018, p. 609).

[94] So did the results of sea sediment studies, which have also been crucial for the extension of the temporal and spatial scales in climate science. On paleoceanography, see Rosol (2015; 2017). Proxy data from ice cores, though, offer a higher temporal resolution of climate information combined with a coverage of an extremely long period from thousands to more than 1 million years in the past (Fischer, 2006).

deep past with concrete climatological events. It gave what historian Matthias Dörries calls "texture" to the deep past.[95]

This temporal extension towards hundreds of thousands of years of climate history also made the cycles of past climatic changes visible. Ice cores, as Antonello and Carey have noted, "shaped temporalities, the senses of time, in the contemporary world."[96] While the understanding of "climate" in 19th-century climatology referred to a rather stable condition, findings such as the "Dansgaard-Oeschger events" showed in detail that climate has changed abruptly in the past. Knowledge about these cycles of past climatic changes (and their causes) gained political importance with the debate on anthropogenic climate change. More importantly here, they shaped the concept of a changing climate with a long history. They helped to expand the temporal scales of climate research far beyond the human experience, and thus contributed to the "loss of human scale" in climate science.[97]

Finally, the vertical perspective also had implications for the horizontal understanding of climate, and reinforced the concept of one global climate system. When Dansgaard published his first papers on his $\delta^{18}O$ studies with rainwater, he made clear that the results depended on "the climatological and geographical conditions … at a given locality."[98] However, with the Greenland core studies, these geographical limitations were lost. When their seminal paper on the Camp Century core appeared in *Science* in 1969, Dansgaard was still careful with his conclusions regarding the global validity of the results, warning Chester Langway: "As to periods of climatology I think one should be careful and not generalize the minor oscillations, like the 120 y period, to be of global validity."[99] Although they eventually decided to add a spatial "warning" to their paper, the conclusion still aimed to be more than local:

> In conclusion, although the complete $\delta(O^{18})$ curve is *primarily valid for the North Greenland area*, the general trend of the curve *agrees with known and reported climatic changes in other parts of the world*, at least in the course of the last 75,000 years. It appears that ice-core data provide far greater, and more direct, climatological details than any hitherto known method.[100]

This ambivalence between the local and global validity of their results seems to mark a transition period for the data interpretation. From then on, the paleoclimatic information from the drilled, punctual cross-sections were interpreted as representative of a large-scale climate imprint. Data from ice cores, sea sediments, and tree rings from various different places in the northern hemisphere seemed to correlate. Furthermore, over the following two decades, different ice cores from the Antarctic indicated similar climatic events in the deep past. This was taken as evidence "that a single deep core may be representative of changes at the continental scale."[101] Scientists subsequently agreed that the atmospheric gases were "well-mixed" and their concentration in the ice bubbles could consequently be understood as global.[102]

As argued above, the ideal drilling site heavily depended on the topographical characteristic of the field and the internal complexity of a given place inside a particular glacier. The individual characteristics of the specific site were crucial, which was why so much effort was invested into the search. However, once safely removed from the field, the ice cores served as universal references for firnification processes and climate, detached from the local features of the specific site where they were drilled. So, on the one hand, the local context of the individual glacier in its full three-dimensional complexity became more and more important for the practicalities of the drilling of an ice core and the dating of the layers. But on the other hand, the conclusions drawn on the reconstructed climate moved away

[95] Dörries (2015, p. 25).
[96] Antonello & Carey (2017, p. 183).
[97] On the "dehumanization" of the climate concept, see Heymann (2018). On the problematic consequences of this discrepancy for practitioners, see also Caseldine (2012).
[98] Dansgaard (1954a, p. 235).
[99] Dansgaard, W. (1969, May 31), Letter to Chester C. Langway, Correspondence of Willi Dansgaard with CRREL/Chet 1959–66, NBI.
[100] Dansgaard, Johnsen, Møller, & Langway (1969, p. 380), my own emphasis.
[101] Lorius et al. (1992, p. 228); See also Jouzel et al. (1989).
[102] Lorius et al. (1992, p. 227).

from this local context. The punctuated vertical insights with a horizontal extent of barely 10 cm have become representative for climatic changes on a large horizontal dimension, nourishing the idea of one global climate. Spatially speaking, the field practice of drilling and the epistemic conclusions of core studies seem to have moved in the opposite direction.

This globalisation of climate was not an isolated process in ice core paleoclimatology, but was strongly linked to the development of climate models. Such models emerged from numerical weather prediction models in the 1950s and 1960s. Due to technical limitations, these so-called General Circulation Models (GCM) represented an ideal atmosphere with a resolution of about 1,000 km.[103] Such coarse representation made it impossible to simulate regional climatic phenomena. The political situation during the Cold War and the rise of environmental concern reinforced the understanding of the earth as a complex and interconnected system, both politically and in terms of environmental pollution. Global climate models seemed appropriate to meet the demand for global knowledge. Soon, they enjoyed high authority in generating climate knowledge and became the dominant research approach in climate science.[104] The "global rhetoric," Antonello and Carey state, was central to establishing "ice core science as meaningful, necessary, and reliable."[105] At the same time, the meaningful and reliable texture of ice core paleoclimatology helped to establish climate models as a successful and eventually dominant tool to study climate dynamics and make projections of future climatic changes.

9 | CONCLUSION

From the 1930s to the 1950s, climatology strengthened its focus on the upper atmosphere. New measuring technologies, such as radiosondes and aeroplanes, provided a vast amount of new observational data on the higher atmospheric layers. They offered an empirical basis for causal explanations of large-scale climate phenomena. Consequently, the classical surface-oriented, two-dimensional approach seemed to become obsolete. Climatologists increasingly began to include the vertical space above our heads in their research, discovering it as an important new dimension. This was the first discovery of the third dimension in climate research.

Between the 1950s and 1970s, ice core science formed as a new glaciological–climatological research field that accessed the vertical dimension downwards, into glaciers. By adopting the stratigraphic method and introducing techniques from physics and geochemistry into glaciology, geophysicists discovered that the depths of glaciers were an archive for deep climate history. With drills and sophisticated infrastructure, they reconstructed changes of temperature and the carbon dioxide content of the atmosphere on a geological time scale. This was the second discovery of the third dimension, this time downwards. Like the first discovery upwards, it profoundly influenced climatological research practices and the understanding of climate and its behaviour.

On the one hand, the discovery of the third dimension downwards was accompanied by important practical and disciplinary developments in both glaciology and climate research. New technology and research techniques expanded the hitherto field-, observation-, and volume-oriented glaciology to encompass physics-based laboratory science. The fruitful interplay between ice coring and climate modelling boosted the success of both fields and helped to transform climatology into a highly interdisciplinary climate science.

Due to the location of the research objects deep inside polar glaciers, expensive technology and equipment mattered enormously. Furthermore, as in the case of the Greenland ice core, the territory was vital to the U.S. military. Hence, since its beginning, ice core research has also depended strongly on international relations and collaboration. Having access to an ice core was scientific capital, and scientific capital was potentially political capital.[106]

[103]On climate modelling, see, among others, Dahan Dalmedico (2001); Edwards (2010; 2011); Heymann, Gramelsberger, & Mahony (2017); Weart (2010); Zorita & Wagner (2018).

[104]On authority of climate models, see, for example, Hulme (2012).

[105]Antonello & Carey (2017, p. 183).

[106]On international collaboration and ice cores as scientific capital see Jouvenet (2016).

In order to access the ice in the vertical, the effective operation of horizontal networks was crucial. Ice core research as vertical glaciology thus made Greenland politically important in its full three-dimensionality. Furthermore, finding the right spot to drill became one of the most important (and expensive) tasks, requiring complex knowledge of the interior functioning of a glacier. The vertical approach led to new knowledge of glacier volumes. The very location of the ice samples, at considerable depths in the polar ice sheets, dictated the research practice and constitution of research groups, in terms of discipline, nationality, and access to funding and territory.

On the other hand, the vertical downwards approach also had far-reaching epistemological consequences. By making the stratigraphic research practice fruitful for glaciology and climatology and turning the vertical into time, ice core scientists reconstructed past climates on a very long time axis. Their high-resolution results expanded the temporal scale in climate science to hundreds of thousands or millions of years, and gave "texture" to this deep climate history. New, detailed knowledge about cycles of climatic changes has revealed that climate has changed rapidly in the past. The classical understanding of climate as a fairly stable or, perhaps, slowly changing state was no longer adequate. Thanks to the high resolution of their data on past climates, the new ice core paleoclimatologists also made it possible to calibrate climate models—a crucial step in improving these numerical models—and eventually helped them to become the dominant climate research tool. Finally, the vertical extension in climate science also influenced the horizontal, geographic concept of climate. From the late 1960s onwards, the geographical limitations on the validity of ice core results were weakened. While the successful drilling in the field turned out to depend on the local conditions of topography and internal structure of an individual glacier, the interpretation of the data became more and more detached from local characteristics. Evidence from the depths of Arctic or Antarctic glaciers indicated that climatic change did not happen only locally, but globally. The discovery of the third dimension downwards reinforced the concept of one global climate with a deep history and subject to abrupt changes.

ACKNOWLEDGEMENTS

I would like to thank the guest editors Martin Mahony and Wilko Graf von Hardenberg for initiating this special issue and inviting me to be part of it. This paper has strongly benefited from their valuable and constructive comments. I also want to express my gratitude to Matthias Heymann and Sarah Dry for their helpful input and stimulating discussions. Furthermore, I thank Hubertus Fischer for sharing his scientific expertise with me and for many important comments on this article, as well as the two anonymous reviewers for their careful reading and constructive feedback.

FINANCIAL SUPPORT

This work was supported by the Swiss National Science Foundation, SNSF (PZ00P1_179883/1).

ORCID

Dania Achermann https://orcid.org/0000-0002-5681-9950

REFERENCES

Ahlmann, H. W. (1935). Contribution to the physics of glaciers. *The Geographical Journal*, *86*, 97–107.

Alley, R. B. (2000). *The two-mile time machine: Ice cores, abrupt climate change, and our future*. Princeton, NJ: Princeton University Press.

Antonello, A. (2018). Glaciological bodies: Australian visions of the Antarctic ice sheet. *International Review of Environmental History*, *4*(1), 125–144.

Antonello, A., & Carey, M. (2017). Ice cores and the temporalities of the global environment. *Environmental Humanities*, *9*, 181–203.

Bader, H. (1939). *Der Schnee und seine Metamorphose: Erste Ergebnisse und Anwendungen einer systematischen Untersuchung der alpinen Winterschneedecke*. Bern, Switzerland: Kümmerly & Frey.

Bader, H. (1949). Trends in glaciology in Europe. *Geological Society of America Bulletin*, *60*, 1309–1314.

Blatter, H., Greve, R., & Abe-Ouchi, A. (2010). A short history of the thermomechanical theory and modelling of glaciers and ice sheets. *Journal of Glaciology*, *56*, 1087–1094.

Caseldine, C. (2012). Conceptions of time in (paleo)climate science and some implications. *Wiley Interdisciplinary Reviews: Climate Change*, *3*, 329–338.

Clarke, G. K. C. (1987). A short history of scientific investigations on glaciers. *Journal of Glaciology*, *33*(S1), 4–24.

Coen, D. R. (2018). *Climate in motion: Science, empire, and the problem of scale*. Chicago, IL: The University of Chicago Press.

Dahan Dalmedico, A. (2001). History and epistemology of models: Meteorology (1946–1963) as a case study. *Archive for History of Exact Sciences*, *55*, 395–422.

Dansgaard, W. (1953). The abundance of O^{18} in atmospheric water and water vapour. *Tellus*, *5*, 461–469.

Dansgaard, W. (1954a). Oxygen-18 abundance in fresh water. *Nature*, *174*, 234–235.

Dansgaard, W. (1954b). The O^{18}-abundance in fresh water. *Geochimica et Cosmochimica Acta*, *6*, 241–260.

Dansgaard, W. (1967). Isotop-undersøgelser af gletschere. *Fysisk Tidsskrift*, *65*, 1–52.

Dansgaard, W. (2005). *Frozen annals: Greenland ice sheet research*. Copenhagen, Denmark: Niels Bohr Institute.

Dansgaard, W., & Johnsen, S. J. (1969). A flow model and a time scale for the ice core from Camp Century, Greenland. *Journal of Glaciology*, *8*, 215–223.

Dansgaard, W., Johnsen, S. J., Møller, J., & Langway, C. C. (1969). One thousand centuries of climatic record from Camp Century on the Greenland ice sheet. *Science*, *166*, 377–381.

Doel, R. D., Harper, K. C., & Heymann, M. (Eds.). (2016). *Exploring Greenland: Cold War science and technology on ice*. New York, NY: Palgrave Macmillan.

Dörries, M. (2015). Politics, geological past, and the future of earth. *Historical Social Research*, *40*(2), 22–36. https://doi.org/10.12759/hsr.40.2015.2.22-36

Edwards, P. N. (2010). *A vast machine: Computer models, climate data, and the politics of global warming*. Cambridge, MA: MIT Press.

Edwards, P. N. (2011). History of climate modeling. *Wiley Interdisciplinary Reviews: Climate Change*, *2*, 128–139. https://doi.org/10.1002/wcc.95

Elzinga, A. (2012). Some aspects in the history of ice core drilling and science from IGY to EPICA. In C. Lüdecke, L. Tipton-Everett, & L. Lay (Eds.), *National and trans-national agendas in Antarctic research from the 1950s and beyond. Proceedings of the 3rd Workshop of the SCAR Action Group on the History of Antarctic Research. BPRC Technical Report No. 2011–01*, (86–115). Columbus, OH: Bird Polar Research Center, Ohio State University.

Elzinga, A. (2015). Making ice talk: Notes from a participant observer on climate research in Antarctica. In S. Maasen & M. Winterhager (Eds.), *Science studies: Probing the dynamics of scientific knowledge* (pp. 181–212). Bielefeld, Germany: Transcript.

Finsterwalder, R. (1959). Expédition glaciologique internationale au Groenland 1957–1960 (EGIG). *Journal of Glaciology*, *26*, 542–546.

Fischer, H. (2006). Editorial: Past, present and future ice core research. *Past Global Changes Magazine*, *14*, 2. https://doi.org/10.22498/pages.14.1

Fischer, H., Severinghaus, J., Brook, E., Wolff, E., Albert, M., Alemany, O., … Wilhelms, F. (2013). Where to find 1.5 million year old ice for the IPICS "oldest ice" ice core. *Climate of the Past*, *9*, 2489–2505.

Fleming, J. R. (1998). *Historical perspectives on climate change*. Oxford, UK: Oxford University Press.

Flohn, H. (1949). Neue Forschungen über die Hochatmosphäre. *Universitas*, *4*, 951–958.

Flohn, H. (1950). Neue Anschauungen über die allgemeine Zirkulation der Atmosphäre und ihre klimatische Bedeutung. *Erdkunde*, *4*, 141–162.

Flohn, H. (1951). Ergebnisse und Probleme der Meteorologie 1940 bis 1950. *Naturwissenschaftliche Rundschau*, *5*, 201–210.

Fristrup, B. (1960a). Den internationale glaciologiske expedition. *Tidsskriftet Grønland*, *1*, 1–15.

Fristrup, B. (1960b). Nogle amerikanske undersøgelse på Grønlands indlandsis. *Tidsskriftet Grønland*, *8*, 281–294.

Fristrup, B. (1960c). Studies of four glaciers in Greenland. *Geografisk Tidsskrift*, *59*, 89–102.

Fristrup, B. (1962). Overvintringsstationer på indlandsisen II: Franske, britiske og amerikanske ekspeditioner 1947–1956. *Tidsskriftet Grønland*, *8*, 298–304.

Fristrup, B. (1977). Thulebasens bagland: Indlandsisen. *Tidsskriftet Grønland*, *9*, 292–306.

Graf von Hardenberg, W., & Mahony, M. (2020). Introduction – Up, down, round and round: verticalities in the history of science. *Centaurus*, *62*.

Haefeli, R. (1959). Die internationale glaziologische Grönlandexpedition 1957 bis 1960 (EGIG). *Schweizerische Bauzeitung*, *77*, 463–468.

Heuberger, J. C. (1954). *Expéditions polaires françaises, Missions Paul-Emile Victor, V: Glaciologie Groënland, Volume 1, Forages sur l'inlandis*. Paris, France: Hermann et Cie.

Heymann, M. (2010). The evolution of climate ideas and knowledge. *Wiley Interdisciplinary Reviews: Climate Change*, *1*, 581–597.

Heymann, M. (2018). The climate change dilemma: Big science, the globalizing of climate and the loss of the human scale. *Regional Environmental Change*, *19*, 1–12. https://doi.org/10.1007/s10113-018-1373-z

Heymann, M., & Achermann, D. (2018). From climatology to climate science in the twentieth century. In S. White, C. Pfister, & F. Mauelshagen (Eds.), *The Palgrave handbook of climate history* (pp. 605–632). London, UK: Palgrave Macmillan UK.

Heymann, M., Gramelsberger, G., & Mahony, M. (Eds.). (2017). *Cultures of prediction in atmospheric and climate science: Epistemic and cultural shifts in computer-based modelling and simulation*. New York, NY: Routledge.

Heymann, M., Knudsen, H., Lolck, M. L., Nielsen, H., Nielsen, K. H., & Ries, C. J. (2010). Exploring Greenland: Science and technology in Cold War settings. *Scientia Canadensis*, *33*(2), 11–42.

Higgins, J. A., Kurbatov, A. V., Spaulding, N. E., Brook, E., Introne, D. S., Chimiak, L. M., … Bender, M. L. (2015). Atmospheric composition 1 million years ago from blue ice in the Allan Hills, Antarctica. *Proceedings of the National Academy of Sciences of the United States of America*, *112*, 6887–6891. https://doi.org/10.1073/pnas.1420232112

Hulme, M. (2012). How climate models gain and Excercise authority. In K. Hastrup & M. Skrydstrup (Eds.), *The social life of climate change models* (pp. 30–44). New York, NY: Routledge.

Ice Drills and Cores. (1957). *Journal of Glaciology*, *3*(21), 30.

Irvine, R. D. G. (2014). Deep time: An anthropological problem. *Social Anthropology/Anthropologie Sociale*, *22*, 157–172.

Jouvenet, M. (2016). From poles to laboratories: Stages in international cooperation in paleoclimatology (1955–2015) (P. Hamilton, Trans.). *Revue Française de Sociologie*, *57*(3), 1–26.

Jouzel, J., Raisbeck, G., Benoist, J. P., Yiou, F., Lorius, C., Rauynaud, D., … Kotlyakov, V. M. (1989). A comparison of deep Antarctic ice cores and their implications for climate between 65,000 and 15,000 years ago. *Quartenary Research*, *31*, 135–150.

Köppen, W. (1895). Die gegenwärtige Lage und die neueren Fortschritte der Klimatologie. *Geographische Zeitschrift*, *1*, 613–628.

Krüger, T. (2008). *Die Entdeckung der Eiszeiten: Internationale Rezeption und Konsequenzen für das Verständnis der Klimageschichte* (Vol. 1). Basel, Switzerland: Schwabe.

Langway, C. C. (1958). A 400 meter deep ice Core in Greenland, preliminary report. *Journal of Glaciology*, *3*, 216–217.

Langway, C. C. (1967). *Stratigraphic analysis of a deep ice core from Greenland* (CRREL Research Report 77). Hanover, Germany: Cold Regions Research and Engineering Laboratory.

Langway, C. C. (2008a). *The history of early polar ice cores* (ERDC/CRREL Report TR-08-1). Retrieved from https://erdc-library.erdc.dren.mil/jspui/bitstream/11681/5296/1/CRREL-TR-08-1.pdf

Langway, C. C. (2008b). The history of early polar ice cores. *Cold Regions Science and Technology*, *52*, 101–117.

Lehmann, P. N. (2015). Whither climatology? Brückner's climate oscillations, data debates, and dynamic climatology. *History of Meteorology*, *7*, 49–70.

Lolck, M. (2006). *Klima, kold krig og iskerner*. Aarhus, Denmark: Aarhus Universitetsforlag.

Lorius, C., Jouzel, J., Raunaud, D., Weller, G., McCave, I. N., & Moore, C. (1992). The ice core record: Past archive of the climate and signpost to the future (and discussion). *Philosophical Transactions: Biological Sciences*, *338*(1285), 227–234.

Lüthi, D., Le Floch, M., Bereiter, B., Blunier, T., Barnola, J.-M., Siegenthaler, U., … Stocker, T. F. (2008). High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature*, *453*(7193), 379–382. https://doi.org/10.1038/Nature06949

Martin-Nielsen, J. (2012). The other cold war: The United States and Greenland's ice sheet environment, 1948–1966. *Journal of Historical Geography*, *38*, 69–80.

Martin-Nielsen, J. (2013). *Eismitte in the scientific imagination: Knowledge and politics at the center of Greenland*. New York, NY: Palgrave Macmillan.

Martin-Nielsen, J. (2016). Security and the nation: Glaciology in early Cold War Greenland. In R. D. Doel, K. C. Harper, & M. Heymann (Eds.), *Exploring Greenland: Cold War science and technology on ice* (pp. 99–118). New York, NY: Palgrave Macmillan.

McPhee, J. (1981). *Basin and range.* New York, NY: Farrar, Strauss, Giroux.

Merchant, P. (2020). Verticalities in oral histories of science. *Centaurus*, *62*.

Miller, M. M. (1951). Englacial investigations related to core drilling on the upper Taku Glacier, Alaska. *Journal of Glaciology*, *1*, 579–580.

Nebeker, F. (1995). *Calculating the weather: Meteorology in the 20th century*. San Diego, CA: Academic Press.

Neftel, A., Oeschger, H., Schwander, J., Stauffer, B., & Zumbrunn, R. (1982). Ice core sample measurements give atmospheric CO_2 content during the past 40,000 yr. *Nature*, *295*, 220–223.

Nielsen, K. H., Nielsen, H., & Martin-Nielsen, J. (2014). City under the ice: The closed world of Camp Century in Cold War culture. *Science as Culture*, *23*, 443–464. https://doi.org/10.1080/09505431.2014.884063

Oeschger, H., Adler, B., & Langway, C. C. (1967). An in situ gas-extraction system to radiocarbon date glaciar ice. *Journal of Glaciology*, *6*, 939–942.

Robin, G. d. Q., & Swithinbank, C. (1987). Fifty years of progess in understanding ice sheets. *Journal of Glaciology*, *33*(S1), 33–47.

Rosol, C. (2015). Hauling data: Anthropocene analogues, paleoceanography and missing paradigm shifts. *Historical Social Research*, *40*(2), 37–66.

Rosol, C. (2017). Data, models and earth history in deep convolution: Paleoclimate simulations and their epistemological unrest. *Berichte der Wissenschaftsgeschichte*, *40*, 120–139. https://doi.org/10.1002/bewi.201701822

Rudwick, M. J. S. (2005). *Bursting the limits of time: The reconstruction of geohistory in the age of revolution*. Chicago, IL: The University of Chicago Press.

Ruuskanen, E. (2018). Encroaching Irish bogland frontiers: Science, policy and aspirations from the 1770s to the 1840s. In J. Agar & J. Ward (Eds.), *Histories of technology, the environment, and modern Britain* (pp. 22–40). London, UK: UCL Press.

Schytt, V. (1954). Glaciology in Queen Maud Land: Work of the Norwegian-British-Swedish Antarctic expedition. *Geographical Review*, *44*, 70–87.

Seligman, G. (1959). Glaciology to-day. *Journal of Glaciology*, *3*, 337.

Sepkoski, D. (2017). The earth as an archive: Contingency, narrative, and the history of life. In L. Daston (Ed.), *Sciences in the archives: Pasts, presents, futures* (pp. 53–83). Chicago, IL: University of Chicago Press.

Simonetti, C. (2013). Between the vertical and the horizontal: Time and space in archaeology. *History of the Human Sciences*, *26*, 90–110.

SIPRE. (1950). *Interim report to Snow, Ice and Permafrost Research Establishment*. Minneapolis, Minnesota: (SIPRE Report I). University of Minnesota, Institute of Technology, Engineering Experiment Station.

SIPRE Research Program. (1957). *July 1, 1957 to December 31, 1958*. US Army, Snow, Ice and Permafrost Research Establishment, Corps of Engineers.

Sorge, E. (1935). Glaziologische Untersuchungen in Eismitte. In K. Wegener (Ed.), *Wissenschaftliche Ergebnisse der deutschen Grönlandexpedition Alfred Wegener 1929 und 1930/31* (Vol. 3, pp. 62–270). Leipzig, Germany: Brockhaus.

Sörlin, S. (2009). The global warming that did not happen: Historicizing glaciology and climate change. In S. Sörlin & P. Warde (Eds.), *Nature's end: History and the environment* (pp. 93–114). New York, NY: Palgrave Mcmillan.

Turchetti, S., Dean, K., Naylor, S., & Siegert, M. (2008). Accidents and opportunities: A history of the radio echo-sounding of Antarctica, 1958–79. *The British Journal for the History of Science*, *41*(3), 417–444.

Weart, S. R. (2010). The development of general circulation models of climate. *Studies in History and Philosophy of Modern Physics*, *41*, 208–217.

White, S. (2015). Unpuzzling American climate: New World experience and the foundation of a new science. *Isis*, *106*, 544–566.

Yan, Y., Ng, J., Higgins, J. A., Kurbatov, A. V., Clifford, H., Spaulding, N. E., … Bender, M. L. (2017, August). *2.7-million-year-old ice from Allan Hills blue ice areas, East Antarctica reveals climate snapshots since early Pleistocene*. Paper presented at the Goldschmidt Conference, Paris, France. Retrieved from https://goldschmidt.info/2017/abstracts/abstractView?id=2017004920

Zorita, E., & Wagner, S. (2018). Analysis and interpretation: Modeling of past climates. In S. White, C. Pfister, & F. Mauelshagen (Eds.), *The Palgrave handbook of climate history* (pp. 141–148). London, UK: Palgrave Macmillan UK.

How to cite this article: Achermann D. Vertical glaciology: The second discovery of the third dimension in climate research. *Centaurus*. 2020;1–24. https://doi.org/10.1111/1600-0498.12294